Chlorpyrifos Exposure and Urban Residential Environment Characteristics as Determinants of Early Childhood Neurodevelopment

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Objectives. We evaluated whether neighborhood characteristics correlated with early neurodevelopment and whether these characteristics confounded the previously reported association between exposure to chlorpyrifos (an organophosphate insecticide) and neurodevelopment.

Methods. We obtained prenatal addresses, chlorpyrifos exposure data, and 36-month Psychomotor Development Index (PDI) and Mental Development Index (MDI) scores for a birth cohort in New York City (born 1998–2002). We used data from the 2000 US Census to estimate measures of physical infrastructure, socioeconomic status, crowding, demographic composition, and linguistic isolation for 1-kilometer network areas around each child's prenatal address. Generalized estimating equations were adjusted for demographics, maternal education and IQ, prenatal exposure to tobacco smoke, caretaking environment quality, and building dilapidation.

Results. Of 266 children included as participants, 47% were male, 59% were Dominican, and 41% were African American. For each standard deviation higher in neighborhood percent poverty, the PDI score was 2.6 points lower (95% confidence interval [CI]=−3.7, −1.5), and the MDI score was 1.7 points lower (95% CI=−2.6, −0.8). Neighborhood-level confounding of the chlorpyrifos-neurodevelopment association was not apparent.

Conclusions. Neighborhood context and chlorpyrifos exposure were independently associated with neurodevelopment, thus providing distinct opportunities for health promotion. (*Am J Public Health.* 2011;101:63–70. doi:10.2105/AJPH.2009.168419)

Developmental delays in early childhood have long-term implications for educational and occupational attainment.[1,2] Environmental characteristics within the household affect neurodevelopment in early life,[3–5] frequently to the disadvantage of vulnerable populations.[6,7] Neighborhood-level environments may also affect neurologic development; indicators of socioeconomic deprivation have been linked to mental or physical health deficits, and these indicators may signal the presence of psychosocial and physical environment risk factors.[8–13] Aspects of neighborhood composition, such as a higher percentage of foreign-born residents, may likewise be associated with the presence of other physical and social environment characteristics relevant to developmental outcomes.[14] Other characteristics with potential relevance to mental development or test performance include crowding of housing units within the neighborhood, exposure to discrimination, and sources of stress that may affect parental caretaking behaviors or parent–child interactions.[15–17]

Studies of environmental effects have identified a number of specific toxic exposures linked to neurodevelopmental deficits,[4,18–20] but the degree to which such associations might be confounded by neighborhood social–environment factors is unknown. Previous studies have reported that exposures to organophosphate pesticides, including chlorpyrifos—which was commonly used in residential settings before the US Environmental Protection Agency banned it for domestic use in 2001—are associated with indicators of poor neurodevelopment in diverse settings[21–28]; however, the association remains controversial[29,30] and may be subject to confounding. Potential confounders of the association between pesticide exposure and neurodevelopment include building dilapidation and poor neighborhood conditions, because both building and neighborhood deterioration are associated with increased pest levels and subsequent increases in pesticide usage.[31,32]

We used data from a birth cohort established by the Columbia Center for Children's Environmental Health in New York City, New York, to explore whether neighborhood conditions and indicators of building dilapidation are independently associated with early childhood neurodevelopment. We hypothesized that exposure to neighborhood-level disadvantage (based on socioeconomic and composition measures, crowding, and psychosocial hazards) or to building dilapidation would be associated with lower psychomotor and mental development scores in this population of inner-city children. We also considered whether neighborhood context could confound the previously reported association of chlorpyrifos with lower psychomotor and mental development scores.[26]

METHODS

Participants for this study were recruited during pregnancy among African American and Dominican women registered at New York Presbyterian Medical Center and Harlem Hospital, both in New York City. A detailed description of the study, which was designed to evaluate the effects of prenatal exposures to ambient and indoor pollutants on birth outcomes, neurocognitive development, asthma, and procarcinogenic damage, has been included in previous reports.[26,33] Briefly, pregnant women aged between 18 and 35 years

were recruited by the 20th week of pregnancy, and their children were born between 1998 and 2002. Women were excluded if they were smokers (classified by self-report) or had a history of drug abuse; if they had diabetes mellitus, hypertension, or known HIV infection; or if they had resided in the New York City area for less than 1 year.

The retention rate at the 3-year follow-up was 83%; those lost to follow-up were not significantly different from continuing participants with respect to maternal age, ethnicity, marital status, education, income, or gestational age and birthweight of the newborn. To both adjust for chlorpyrifos exposure in our models of neighborhood conditions and examine the possibility that the chlorpyrifos association with psychomotor development was confounded by neighborhood or building conditions, we restricted our analytic sample to children with completed assessment of both chlorpyrifos exposure and developmental outcomes. Of 327 children with a completed developmental assessment at approximately 36 months of age, 266 (81%) had chlorpyrifos exposure data available and were included in our analyses. Children excluded for missing chlorpyrifos exposure data were similar to the analytic sample except that excluded children had more indicators of building dilapidation (mean of 1.3 versus 1.0 indicators reported; $P<.001$).

Housing and Neighborhood Characteristics

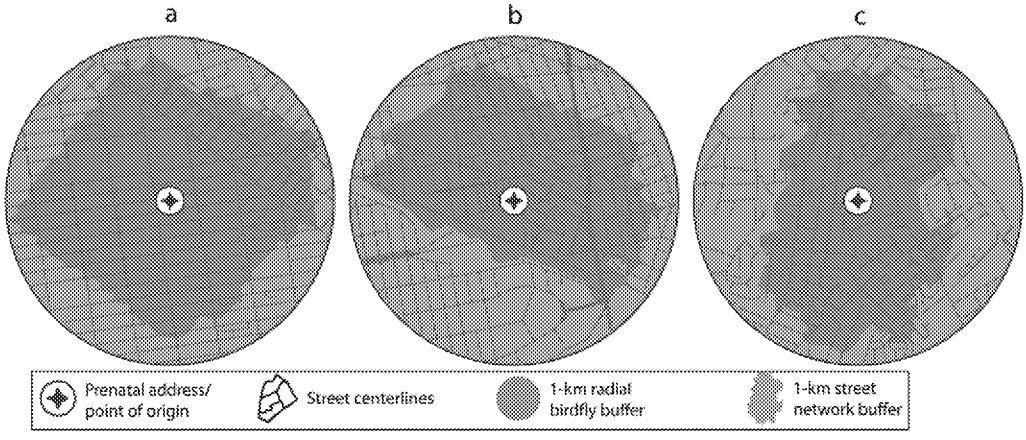
Indicators of building disrepair were self-reported by mothers during the prenatal interview[31] and summed to create an index that included 1 point for each of the following problems: holes in ceilings or walls, peeling or flaking paint, water damage, leaking pipes, and lack of gas or electricity in the prior 6 months. This index of disrepair ranged from 0=no problems to 4=4 or more problems.

Each participant's prenatal home address was also geocoded using Geosupport, a software package developed by the New York City Department of City Planning. A 1-kilometer network buffer was selected as our main neighborhood definition.[34–37] We constructed the network buffer by following the street network for 1 kilometer in every direction from the geocoded address and then joining these points together to create a polygon (Figure 1). To assess the sensitivity of the results to different definitions and constructions of "neighborhood," we also constructed 1-kilometer, 0.5-kilometer, and 0.25-kilometer radial (circular) buffers.

The network and radial buffers were characterized using block-group data and a spatial overlay. All measures of neighborhood context were derived from the US Census data for the year 2000, summary file 3.[38] Network buffer characteristics included the percentage of housing units that were without complete plumbing, the percentage of housing units that were vacant, the percentage of individual residents who were below the federal poverty line, the percentage of residents aged older than 25 years who completed high school or its equivalent, the percentage of households receiving public assistance, the percentage of housing units that were crowded (defined as 1 or more residents per room), the percentage of residents who reported their race as Black, the percentage of residents who reported their race as White, the percentage of residents born outside the United States, the percentage of residents who spoke Spanish, and the percentage of residents who were linguistically isolated (the US Census Bureau defines a household as linguistically isolated if all household members aged 14 years and older have at least some difficulty with English).

Child and Maternal Characteristics

The Bayley Scales of Infant Intelligence–Revised (BSID-II) were used to assess cognitive and psychomotor development at age 36 months.[39] This test was selected because it is a widely used norm-referenced developmental test for young children, it can be used to diagnose developmental delay, and it is known to be sensitive to the effects of toxic exposures such as low-level intrauterine lead.[40] Each scale provides a developmental quotient (raw score divided by chronological age) that generates



Note. Street network buffers use the street network as the organizing geography, on the basis of the idea that people use the street network to move about a city. A destination that is 1 kilometer away as the crow flies may be several times that far in an area with a winding or discontinuous street pattern.

Figure 1—Network buffers around addresses in (a) Brooklyn, (b) the Bronx, and (c) Staten Island: New York City, NY, 1998–2002.

a Psychomotor Development Index (PDI) and a Mental Development Index (MDI). When administered at age 3 years, the BSID-II demonstrates only moderate predictive power for subsequent intelligence and school performance, but it is clinically useful for children performing in the subnormal range.[39,41,42] The minimum possible score on each scale is 50, and the maximum possible score is 150. Children can be classified as normal (greater than 85) or delayed (85 or less) based on standardized cutpoints. In the present study, each child was tested under controlled conditions in the study office by a trained bilingual research assistant whose results were checked for interobserver reliability.

A trained bilingual interviewer administered a 45-minute prenatal interview to each woman during the third trimester of her pregnancy. The interview, which was adapted from a related study in New York City,[43] included questions on demographic and socioeconomic characteristics, lifetime residential history, smoking history, history of pesticide use, and characteristics of the home environment. When the child was aged approximately 36 months, the Test of Nonverbal Intelligence[44] (second edition) was used to assess maternal intelligence, and the Home Observation for Measurement of the Environment (HOME)[45] instrument was used to assess the quality of the caretaking environment. The HOME quality score integrates information on physical and interactive aspects of the environment, including parental interactions with the child and play materials that provide a variety of stimulation.

Chlorpyrifos Exposure

Maternal and umbilical cord plasma samples were used to measure chlorpyrifos exposure, as described previously.[33] Umbilical cord plasma concentration was estimated directly (for the 88% of children whose umbilical cord blood was collected at delivery) or estimated from maternal plasma levels (for the 12% of children lacking umbilical cord blood samples but whose mothers had given blood samples within 2 days of delivery). A heparin-containing syringe or tube was used to prevent clotting, and laboratory assays were conducted at the Columbia Center for Children's environmental health laboratory.[46] Chlorpyrifos exposure was classified as high if the value was in the highest tertile of detectable concentrations (greater than 6.17 pg/g).

Statistical Analysis

Intraclass correlation coefficients (ICCs) were used to evaluate how development scores varied between community districts (which are named neighborhood units within New York City) and census tracts versus variation within districts and tracts. These ICCs can be interpreted as the maximum proportion of variation in development scores that could be explained at the given group level.[47] If a characteristic was constant within each group, the only variation would be between groups, and the ICC would be 1.0. In contrast, if the characteristic was randomly distributed with respect to group, the ICC would be close to 0. These estimates were based on 1-way analysis of variance models. Community districts were selected for ICC analysis and to account for clustering on the basis of their salience as named areas of New York City (n=59 community districts across all 5 boroughs, 16 of which included 1 or more prenatal address for our study population), and census tracts were selected to look at more localized clustering (prenatal addresses in the study were located within 96 census tracts). Census tracts are relatively small within the context of New York City, with a median area of 0.18 square kilometers.[48]

Generalized estimating equation models were created for the continuous outcomes (PDI and MDI). Robust standard errors were used to correct for possible autocorrelation within community district areas. All models included the following potential confounders: gender, gestational age at birth, Dominican versus African American ethnicity, maternal education, maternal intelligence quotient, the presence of secondhand smoke in the home during pregnancy, and an index of the quality of the home environment with respect to caretaking. Missing data on covariates (gestational age at birth, n=9; maternal intelligence quotient, n=34; secondhand smoke in the home, n=4; and the quality of the caretaking environment, n=27) were filled in by multiple imputation.[49,50] Five imputed datasets were created using all variables from our analytic model, and the results from these imputed datasets were recombined such that regression confidence intervals reflected the degree of uncertainty from missing covariate data.[50] All analyses were completed using Stata version 9.2 (StataCorp LP, College Station, TX).

RESULTS

Of the 266 children included, 47% were male, 59% were Dominican, and 41% were African American (Table 1). All prenatal addresses were located in northern Manhattan or the south Bronx. Every 1-kilometer circular buffer around each child's prenatal address (referred to hereafter as a "neighborhood") was characterized by concentrated poverty, with at least 20% of the residents

TABLE 1—Child, Maternal, Household, and Neighborhood Characteristics of Children Born in New York City, NY: 1998–2002

Characteristic	% or Mean (SD)
Male	47
Dominican	59
African American	41
Mother completed high school	65
Gestational age at birth, wk	39.4 (1.3)
Maternal intelligence quotient	86 (14)
Bayley's PDI at 36 mo	100 (13)
Bayley's MDI at 36 mo	90 (12)
Prenatal environment	
High chlorpyrifos exposure[a]	19.5
Tobacco smoke in the home	37.8
HOME score[b]	39.7 (5.7)
Indicators of disrepair	1.3 (1.3)
Characteristics of 1-km network buffers around prenatal addresses	
% poverty	35.5 (4.4)
% high school graduates	25.9 (6.0)
% African American	42 (25)
% linguistic isolation	20.7 (9.2)
% crowded household	22.7 (7.0)
% inadequate plumbing	2.42 (0.42)
% vacant housing	7.5 (3.8)

Note. HOME = Home Observation for Measurement of the Environment; MDI = Mental Development Index; PDI = Psychomotor Development Index. The total sample size was N = 266.
[a]High chlorpyrifos exposure was defined as an estimated umbilical cord plasma concentration greater than 6.17 pg/g.
[b]Integrates information on physical and interactive aspects of the environment, including parental interactions with the child and play materials that provide a variety of stimulation.

estimated to be below the federal poverty line (Table 1).

The geographic variation in development score as assessed using ICCs was low at both the community district level (for PDI, ICC=0.03; 95% confidence interval [CI]=0.00, 0.09; for MDI, ICC=0.04; 95% CI=0.00, 0.12) and the census tract level (for PDI, ICC=0.05; 95% CI=0.00, 0.18; for MDI, ICC=0.04; 95% CI=0.00, 0.18), suggesting limited spatial clustering and autocorrelation for our continuous outcomes.

Neighborhood Context, Housing Disrepair, and Neurodevelopment

Adding neighborhood characteristics to a model with individual and household characteristics improved model fit, as indicated by a higher R^2 value. For example, adding neighborhood socioeconomic characteristics (percent of residents below the federal poverty line and percent with a completed high school education) explained an additional 2.2% and 1.5% of the variation in PDI and MDI, respectively (Table 2 and Table 3). Socioeconomic deprivation—and percent poverty in particular—was the neighborhood characteristic most consistently associated with PDI and MDI. Each standard deviation increase in neighborhood percent poverty was associated with a 2.6-point decrease in PDI score (Table 2) and a 1.7-point decrease in MDI score (Table 3). Neighborhood percent poverty remained independently associated with PDI (P=.01) but not with MDI (P=.56) for models that included all other neighborhood domains (neighborhood composition, linguistic isolation, crowding, and physical infrastructure) as well as individual income (data not shown).

The index of housing disrepair was significantly associated with MDI but not with PDI, and the association was not in the hypothesized direction (Table 2 and Table 3); each additional indicator of disrepair was associated with a 0.7-point increase in MDI.

Neighborhood Context, Chlorpyrifos, and Neurodevelopment

In this inner-city population, children born before the January 2001 implementation of the ban on chlorpyrifos for domestic use were more likely to have high chlorpyrifos exposure (51 out of 180 births had high chlorpyrifos exposure) compared with children born after the ban (1 out of 86 births had high chlorpyrifos exposure). Children without high prenatal chlorpyrifos exposure who were born in either of the preban or postban periods had a mean PDI score of 101, whereas children with high chlorpyrifos exposure had a mean PDI score of 95. Likewise, the mean MDI score was similar for children without high prenatal chlorpyrifos exposure who were born in either of the preban or postban periods (increasing from 90 preban to 91 postban), and these scores were higher than the mean MDI score for children with high chlorpyrifos exposure (88). (The mean values for children with high chlorpyrifos exposures are unchanged if we exclude the 1 child who had high chlorpyrifos exposure despite being born after the ban.)

Although high chlorpyrifos exposure was not significantly associated with any of the neighborhood characteristics considered, participants with high chlorpyrifos exposure tended to live in areas with more poverty (mean difference 1.3%; P=.06). As previously reported,[51] after we controlled for gender, gestational age at birth, ethnicity, maternal education, maternal intelligence quotient, exposure to secondhand smoke in the home during pregnancy, and the quality of the home environment, high chlorpyrifos exposure (greater than 6.17 pg/g) was associated with a 6.5-point decrease in PDI and a 3.3-point decrease in MDI at age 36 months.[51] These associations remained statistically significant and similar in magnitude after accounting for dilapidated housing and neighborhood characteristics (Table 2 and Table 3).

TABLE 2—Associations of 36-Month Psychomotor Development Index Scores With Neighborhood Characteristics, Building Disrepair, and Chlorpyrifos Exposure of Children Born in New York City, NY: 1998–2002

	Model 1, B (95% CI)	Model 2, B (95% CI)	Model 3, B (95% CI)	Model 4, B (95% CI)	Model 5, B (95% CI)	Model 6, B (95% CI)
% poverty		-2.6 (-3.7, -1.5)				
% high school graduates		-1.2 (-2.4, 0.1)				
% African American			-1.3 (-2.5, 0.0)			
% linguistic isolation				0.7 (-0.1, 1.6)		
% crowded household					0.0 (-0.9, 1.0)	
% inadequate plumbing						-0.8 (-2.0, 0.3)
% vacant housing						0.1 (-1.1, 1.3)
Index of building disrepair	0.6 (-0.4, 1.7)	0.5 (-0.5, 1.4)	0.6 (-0.4, 1.6)	0.6 (-0.4, 1.7)	0.6 (-0.4, 1.7)	0.6 (-0.4, 1.7)
High chlorpyrifos exposure	-6.9 (-11.1, -2.7)	-7.0 (-11.0, -2.9)	-7.3 (-11.5, -3.0)	-7.2 (-11.3, -3.0)	-6.9 (-11.1, -2.8)	-7.1 (-11.4, -2.7)
Model fit (R^2)	0.126	0.148	0.129	0.127	0.126	0.128

Note. CI = confidence interval. The total sample size was N = 266. Model 1 was individual and household characteristics, model 2 was model 1 characteristics plus socioeconomic context, model 3 was model 1 characteristics plus neighborhood composition, model 4 was model 1 characteristics plus neighborhood linguistic isolation, model 5 was model 1 characteristics plus neighborhood crowding, and model 6 was model 1 characteristics plus neighborhood physical infrastructure. Regression coefficients are from generalized estimating equation models that adjust for gender, gestational age at birth, Dominican ethnicity, maternal education, maternal intelligence quotient, the presence of secondhand smoke in the home, and an index of caretaking environment quality. All neighborhood characteristics have been standardized, and the corresponding regression coefficients can be interpreted as the mean point increase in Psychomotor Development Index scores for an increase by 1 standard deviation in the neighborhood value of the given characteristic. Multiple imputation was used to fill in missing covariate values and to account for the uncertainty caused by missing data.

TABLE 3—Associations of 36-Month Mental Development Index Scores With Neighborhood Characteristics, Building Disrepair, and Chlorpyrifos Exposure of Children Born in New York City, NY: 1998–2002

	Model 1, B (95% CI)	Model 2, B (95% CI)	Model 3, B (95% CI)	Model 4, B (95% CI)	Model 5, B (95% CI)	Model 6, B (95% CI)
% poverty		-1.7 (-2.6, -0.8)				
% high school graduates		-1.0 (-2.1, -0.0)				
% African American			-0.2 (-1.4, 0.9)			
% linguistic isolation				-0.3 (-1.3, 0.7)		
% crowded household					-0.8 (-1.8, 0.3)	
% inadequate plumbing						0.2 (-1.1, 1.5)
% vacant housing						0.3 (-0.6, 1.3)
Index of building disrepair	0.7 (0.1, 1.3)	0.6 (0.2, 1.1)	0.7 (0.1, 1.3)	0.7 (0.1, 1.4)	0.7 (0.1, 1.3)	0.7 (0.1, 1.3)
High chlorpyrifos exposure	-3.2 (-5.1, -1.3)	-3.4 (-5.2, -1.5)	-3.2 (-5.0, -1.5)	-3.1 (-4.8, -1.3)	-3.0 (-4.8, -1.2)	-3.2 (-5.1, -1.3)
Model fit (R^2)	0.263	0.278	0.263	0.263	0.267	0.264

Note. CI = confidence interval. The total sample size was N = 266. Model 1 was individual and household characteristics, model 2 was model 1 characteristics plus socioeconomic context, model 3 was model 1 characteristics plus neighborhood composition, model 4 was model 1 characteristics plus neighborhood linguistic isolation, model 5 was model 1 characteristics plus neighborhood crowding, and model 6 was model 1 characteristics plus neighborhood physical infrastructure. Regression coefficients are from generalized estimating equation models that adjust for gender, gestational age at birth, Dominican ethnicity, maternal education, maternal intelligence quotient, the presence of secondhand smoke in the home, and an index of caretaking environment quality. All neighborhood characteristics have been standardized, and the corresponding regression coefficients can be interpreted as the mean point increase in Mental Development Index scores for an increase by 1 standard deviation in the neighborhood value of the given characteristic. Multiple imputation was used to fill in missing covariate values and to account for the uncertainty caused by missing data.

Neighborhood poverty did not significantly modify the association of chlorpyrifos exposure with PDI (P=.4) or MDI (P=.2) in this population. The interaction analyses suggested that the association between our standardized neighborhood percent poverty variable and PDI was attenuated from –2.5 in children with lower chlorpyrifos exposure to –1.2 in the presence of high chlorpyrifos exposure, representing a difference of 1.3 units PDI per standard deviation (95% CI=–1.7, 4.4). Likewise, interaction analyses for the outcome of MDI suggested attenuation from –1.7 in children with lower chlorpyrifos exposure to zero in the presence of high chlorpyrifos exposure (a difference of 1.6 units; 95% CI=–1.2, 4.5). In both cases, the CIs do not allow us to rule out zero interaction, but they do allow us to rule out a large amplification of the neighborhood poverty association in the presence of high chlorpyrifos exposure.

Additional Analyses

Sensitivity analyses were conducted to evaluate the robustness of these associations to the use of alternative neighborhood definitions. In a phenomenon known as the "modifiable areal unit problem," the associations among neighborhood-level variables may depend in part on how neighborhoods are defined[52,53]; thus, switching neighborhood definitions has the potential to alter the role a given variable plays in predicting the outcome or confounding other associations of interest. Analyses were repeated using radial buffers of 1 kilometer, 0.5 kilometer, and 0.25 kilometer in diameter; regardless of the scale chosen, measures of the quality of housing stock and individual-level measures of dilapidation did not confound the effect of chlorpyrifos exposure on PDI. Across these models, high chlorpyrifos exposure was significantly negatively associated with PDI. For smaller buffer sizes, percentage of homes with inadequate plumbing (for the 0.5-kilometer buffer only) and neighborhood Black racial composition (for the 0.25-kilometer buffer only) had statistically significant inverse associations with PDI (data not shown). Results were also similar in models using only those subjects (n=202) with complete individual-level covariate data.

DISCUSSION

In this high-risk New York City birth cohort, the inclusion of variables for neighborhood characteristics improves our ability to explain the variation in early childhood psychomotor and mental development. Among the neighborhood characteristics considered, we found that economic deprivation as indicated by the percentage of individuals in poverty was independently associated with lower values for both PDI and MDI. Neighborhood poverty appeared to function as an independent predictor of less neurodevelopment, and neighborhood poverty did not confound or modify the association between chlorpyrifos exposure and neurodevelopment in this population.

The finding that neighborhood poverty predicted lower psychomotor and mental development scores is consistent with previous studies showing that neighborhood poverty predicts neurodevelopment[54] or mental health in childhood.[12] The effects of neighborhood poverty on adult physical health and stress[9,55–57] may also indirectly impede the development of children in these neighborhoods by altering parent-child interactions.[16] Likewise, linguistic isolation, crowding, and physical infrastructure problems may affect adult health or stress levels, thus impairing subsequent parent-child interactions that are crucial to healthy development.[16]

Concentrated poverty, a fundamental cause of poor health,[58,59] may cause people in some areas to be more exposed to relevant toxicants such as lead paint, pesticides, and secondhand smoke. However, we found that the association between neighborhood poverty and psychomotor development was independent of measured exposure to chlorpyrifos[51] and secondhand

smoke.[26] A similar but weaker association was observed for MDI, suggesting that this more general mental development score may be less sensitive to these aspects of the environment than the psychomotor development measure. Housing dilapidation, on the other hand, was not associated with lower cognitive scores as hypothesized; instead we observed an association in the unexpected direction that was statistically significant for our models of MDI. This unexpected finding that maternal reports of building problems were associated with better mental development could be attributable to chance; another plausible explanation is that the self-reported dilapidation scale is serving as a proxy for a protective maternal characteristic, such as attention to problems in the child's environment.

Previous studies of prenatal chlorpyrifos exposure and neurological development have failed to consider the potential impact of individual housing and neighborhood-context variables on the exposure–development association. It is important to control for possible confounding effects of these social and physical conditions in studies of neurotoxicity because social adversity and other poverty-related variables, including housing, are very likely to be associated not only with chemical exposures but also with the developmental outcome of children. That is, such physical living conditions may contribute independently to developmental outcomes, and they may also confound other exposure–outcome associations.

An important question is whether exposure to specific chemicals is associated with cognitive or attentional deficits, beyond those deficits that might be attributed to the other aspects of the social and physical environment. To address this question, data must be collected at multiple levels; in the current study we collected data at the individual, household, and neighborhood levels. Further, the exposures one wishes to distinguish must not be perfectly correlated. In our study, high chlorpyrifos exposure was only weakly associated with neighborhood poverty; this link between exposures of interest may have been weakened by the strong secular trend across all study neighborhoods toward decreasing chlorpyrifos exposure after the ban on domestic use. In our study, chlorpyrifos remained associated with developmental outcomes after we controlled for other individual-level and neighborhood-level variables. These results argue against the presence of noncausal explanations based on differences in housing quality and sociodemographic context for the chlorpyrifos–neurologic development relationship.

Strengths and Limitations

A key strength of our study came from the prospective data on prenatal residential locations from this birth cohort, allowing us to avoid sources of measurement bias that may be problematic for retrospective study designs. Another strength was the detailed assessment of the physical and caretaking environment within each child's home. Furthermore, the research used individualized definitions of the children's neighborhoods rather than arbitrarily determined administrative boundaries such as zip codes or US census tracts. The models, based on data from geographic information systems, built neighborhood areas around the child's home by using the street network to define all areas the child could reach within 1 kilometer of the home. This methodology does not allow the defined neighborhood to cross natural barriers in the environment, such as the cliff faces that are prevalent in northern Manhattan, or to cross boundaries such as highways or rivers.

To test the robustness of the findings, analyses were repeated using several other methods to define "neighborhood." In addition, generalized estimating equations with robust standard errors were used to account for autocorrelations among variables that might occur within community districts. This accounts for nonindependence of neighborhood variables arising, for example, from the fact that residents of Hunts Point in the south Bronx are more similar to each other than they are to residents of Washington Heights in northern Manhattan. Finally, the ban on domestic use of chlorpyrifos that went into effect during our study period introduced exogenous variation to this exposure of interest.

Our study was limited by its observational study design, making causal inference challenging. In particular, the prenatal exposures considered may have been correlated with aspects of the postnatal environment, limiting our ability to estimate a cumulative exposure dose or to investigate periods that may have been developmentally sensitive in the child's early life. Also, the sample for this study was, by design, drawn from low-income African American and Dominican communities. This vulnerable population may have had a more restricted range of relevant exposures than the general population, and our statistical power to assess associations with neighborhood characteristics was limited by the restriction of the study sample to low-income communities. The generalizability of our study results is further limited because participants were recruited from a restricted range of neighborhoods in New York City.

Conclusions

Our findings suggest that early childhood developmental delay, which may have long-term consequences for educational attainment and health, was affected by the prenatal environment. Prenatal measures of both neighborhood poverty and chlorpyrifos exposure were independently associated with lower developmental scores in low-income New York City neighborhoods largely populated by minorities. The previously reported association between chlorpyrifos exposure and neurodevelopmental delay was not substantially attenuated when we accounted for indicators of building disrepair and for a range of neighborhood characteristics considered to be potential confounders of the association. The results were consistent regardless of adjustment for multiple neighborhood characteristics, as measured using different definitions of neighborhood. The integration of neighborhood context measures into health studies offers the potential to identify modifiable health determinants in the form of local resources or hazards. Neighborhood context measures can also either substantiate or ameliorate concerns about confounding in investigations of specific chemical toxicants or indoor environmental exposures. Finally, large studies that collect both neighborhood context and exposure data could reveal patterns of effect modification that increase our understanding and allow public health efforts to be strategically deployed. ■

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Contributors

All authors contributed to the study design, analytic approach, and interpretation of results. G.S. Lovasi conducted the statistical analyses, with assistance from L. Hoepner and A. Rundle. G.S. Lovasi prepared the article, with assistance from V.A. Rauh and A. Rundle. J.W. Quinn constructed the neighborhood measures. All authors critically reviewed and revised article drafts and approved the final version.

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Human Participant Protection

All study procedures were approved by the institutional review board of Columbia University, and informed consent was obtained from all participants.

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